Damage Evolution Studies in Carbon Fiber Reinforced Polymer Composites using Active and Passive Thermography

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Abstract

The increasing demand for using advanced composite materials in critical load bearing components in a variety of structures under different loading conditions requires great efforts in various research areas such as development of methodologies for life prediction, characterization of damage evolution and mechanisms at multiple scales. These complicated issues are still long-term goals; however, in recent years research activity has been devoted to the application of non-destructive evaluation techniques for the characterization of damage progress and failure mechanisms in composite materials. Among the nondestructive testing methods, infrared thermography is a non-invasive technique suited for real time monitoring and gives in-situ information regarding the onset and damage growth. The objective of this work is to use infrared thermography to predict the initiation of damage and their evolution of carbon fiber reinforced polymer composite specimens under static loading condition. To quantify the damage evolution under tensile loading, the load is applied in steps followed by dwell period at each load step. During the tensile testing, the thermal images are recorded through an infrared camera to measure the temperature evolution in carbon fiber reinforced polymer (CFRP). Both active and passive thermography techniques are used to study the damage initiation and propagationunder static loading condition. Post processing of the thermal images obtained using thermography techniques are used to quantify the damage in unidirectional CFRP specimens.
Keywords: Non-destructive evaluation,Active Thermography, Passive Thermography, Composites.

1. Introduction

Composite materials are increasingly used in the field of aerospace, marine, automobile and wind energy applications due to their high specific strength & stiffness properties and tailorability optionsto design efficient structures. Recently,advancedcarbon fiber-reinforced polymer matrix composites have been widely used in primary and secondary load bearing aircraft structures. Composites usage in critical structures necessitatesa clearunderstandingof their mechanical behavior under static and dynamic loading. Unlike metals, composite materials are inhomogeneous andanisotropic which makes theirfailure more complex and understanding those leads to more efficient design[1].In addition defectsoriginated during the manufacturing process, also affect the mechanical behavior of these materials. Various intrinsic and extrinsic factorsaffect the mechanical behavior of composites and very difficult to define damage models, which can be used to make life estimation of these materials. For these reasons, nondestructive testing and evaluation of composites is essential for damage monitoring, and their quantification [2].

Thermal imaging or infrared thermography is one among the widely used nondestructive testing and evaluation technique in aerospace, mechanical, and civil engineering structures. Infrared thermography is a nonintrusive techniquethat works on the acquisition and image processing of thermal information recorded by non-contact measurement devices [3].Image processing of the acquired thermal images provides qualitative and quantitative information about the presence of damage in structures. With the advent of technology, thermal imaging has evolved andhas become an effective tool to identify the critical zone well before the failure [4]. There are two approaches in infrared thermography,

i) *Active*, in which the features of interest are naturally at a higher or lower temperature than the background; and
ii) *Passive,* in which an energy source is require producing a thermal contrast between the feature of interest and the background [5].

The objective of this work is to use infrared thermography to predict the initiation of damage and their evolution of CFRP composite specimens under static loading condition. To quantify the damage evolution under tensile loading, the load is applied in steps followed by dwell period at each load step. During the tensile testing, the thermal images are recorded through an infrared camera to measure the temperature evolution in CFRP. Both active and passive thermography techniques are used to study the damage initiation and propagation under static loading condition. Post processing of the thermal images obtained using thermography techniques are used to quantify the damage in CFRP of unidirectional layup configurations.

2. Composite Fabrication

Composite specimens were fabricated using hand layup and vacuum bagging technique. Dimension of the specimen and the tab is shown in fig 1.For tab material for the CFRP specimens, glass fiber reinforced plastic composite is used. For matrix material, epoxy resin of Araldite CY230 and hardener of Araldite HY951 with a ratio of 10:1 was used. For curing, the specimens werekept under vacuum pressure of - 89 kPa at room temperature of 25.7˚C for 24hrs.After curing, the thickness of the specimen was measured to be 1.7 mm.

3. Data Acquisition

3.1. Experimental Setup

Tensile test on the CFRP coupons were carried out using MTS universal testing machine. The test specimens were loaded in steps consisting of 10 cycles, including dwell phase (constant displacement) as shown in fig 2. The tensile test was carried out at crosshead speed of 0.50mm/min for the all ramps to achieve the desired stress level of 440 MPa at each step. At each level, a displacement increment of 0.75 mm was chosen. Passive thermography was performed during the ramp loading and active thermography during the dwell stage. FLIR SC5500 camera is used for acquiring the thermal images, which is having maximum of 320x256 pixel resolution, 3-5μmspectral range, up to 20mk thermal sensitivity. The camera was placed at a distance of 500 mm from the specimen and focus of the camera was adjusted to the center of the specimen to avoid the heat transfer from the grip areas. The temperature range, integration time and frame rate were chosen to be 21˚C to 91˚C, 400 μs and 150 Hz respectively. The testing setup is shown in fig. 3. The image processing of the recorded data was performed by using Altair, a software developed by FLIR System.

Among various active thermography methods, the lock-in thermography was considered for this study. For lock-in thermography, two optical lamps were used, each having a capacity of 2.5 KW, placed at a distance of 650 mm from the specimen. Using AT-IrNDT software, the lamps were triggered through NI-IRX box which acts as an interface between the software and the IR camera and lamps. Practically, any frequency in the range from 0.01 to 0.09 Hz can be used for lock-in thermography.For excitation of the lamps, a sinusoidal waveat a frequency of 0.01 Hzwas used in this study. Selection of excitation frequency depends upon various parameters like, specimen thickness, stacking sequence, material properties etc. To reduce the noise, three period of excitation was chosen and image acquisition rate was chosen as 50 Hz.

3.2. Image Processing

3.2.1. Passive Thermography

The contrast of the thermal images acquired can be improved using variousimage processing techniques and this provides information regarding the damage evolution in composites during loading. The sequence of thermal images arenormalized, dividing all recorded frames by the first one in each sequence. This operation is performed through Altair software (FLIR), which allows theuser to perform image processing on the acquired thermographic images.

$$\overline{F_i} = \frac{F_i}{F_0} \qquad (1)$$

where, $\overline{F_i}$ represent the normalized image ofi^{th} frame in the normalized image sequence, F_i represent the raw thermogram image at the i^{th} frame in the raw thermogram image sequence and F_0 represent the starting frame of the raw thermogram image sequence.To identify the temperature difference generated by the local heat dissipation atspecific location, it is necessary to calculate the temperature difference. Taking into consideration, temperature normalization, temperature difference could becalculated as:

$$\overline{\Delta T} = \overline{T}(\overline{F_i}) - \overline{T}(\overline{F_{i-1}}) \qquad (2)$$

where, $\overline{\Delta T}$represent the normalized temperature difference, $\overline{T}(\overline{F_i}), \overline{T}(\overline{F_{i-1}})$represents the normalized temperature at the $i^{th}$and i-1^{th}frame in the normalized sequence respectively [6].

3.2.2. Lock-in Thermography

Different techniques have been developed to study the thermal images obtained using lock-in thermography. Fourier analysis is the preferred processing technique since it provides single image, ampligram or phasegram (the weighted average of all the images in a sequence). The resulting signal-to-noise ratio (SNR) is therefore very high. Phase data in particular is very interesting in nondestructive testingand evaluation as it is less affected than raw thermographic data by non-uniform heating, emissivity variations at the surface, reflections from the environment and surface geometry [7].

In lock-in thermography, the system collects a series of image and compare them to obtain amplitude and phase of the sinusoidal wave pattern at each point, resulting in an amplitude ora phase image. If S_1, S_2, S_3 and S_4 are four equidistant thermographic images in a completeperiod, then the phase (∅) and amplitude (A) are given by [8],

$$\emptyset = \tan^{-1}\left(\frac{S_1 - S_3}{S_2 - S_4}\right) \tag{3}$$

$$A = \sqrt{(S_1 - S_3)^2 + (S_2 - S_4)^2} \tag{4}$$

The phase (∅) and amplitude (A) are computed using IrNDTsoftware from automation technology.

4. Result & Discussion

Initially passive thermography technique was used to investigate the thermo-elastic effect. First a qualitative analysis was performed, by analyzing the thermal maps to found out the critical zone(High Temperature in fig 4) in the specimenby analyzing the thermal profile. The mean temperature data of the selected critical zonewere extracted and the temperature differenceΔT (°C) ($\Delta T = T_i - T_0$)for the whole thermal flim is obtained, considering initial temperature as $T_0 = 24.18$ °C.Thetime versus ΔT andstress plot shown in Fig 6, clearly demonstrate the thermos-elastic effectwhich states linear relationship between the stress state of a material under adiabatic conditions and its temperature variation ($\Delta T = -K_m T \sigma_m$).The thermomechanical behavior of the compositeisdivided into three zones, an initial region(Zone I), characterized by an approximately linear decrease in temperature and elastic behavior, where the mechanical energy oftesting is completely stored by the material. In Zone II, a non-linear mild decrease in temperature with elastic mechanical behavior was observed andpossibly small matrix cracks are created in this region.In final region, the temperature increases until the final failure and the energystored is released to create new cracks and enlargethe existing ones. Fig 5, illustrate the different zones and their corresponding thermographs are shown in Fig 7, 8, 9 and 10 respectively. In addition, it is observed that the stress value corresponding to the point where the temperature profile becomes non-linear represent the damage stress, which in this case, is 210 MPa. For additional information regarding the damage distribution and their evolution active thermography was employed.

4.1. Combined Passive and Active Thermography Test Analysis

The results at the end of firstload step for the combined passive and active thermography are shown in Fig. 11.The normalized – subtracted image (Fig 11 (a)) obtained from passive thermography wasable to capture matrix cracks highlighted as hot spots without much clarity.Furthermore, lock-in thermography (Fig 11 (b)) shows more clearly the matrix crack information from the phase image and clearly indicates the zone where the specimen has actually failed (Fig 11 (c)).

5. Conclusion:

In this paper, the application of passive andlock-in infrared thermography were used for the study of damage evolution in unidirectional CFRP under static loading condition.Passive thermography provides information regarding the variation of stress and temperature with load and also stress at which the damage initiates.Lock-in thermography provides information regarding the damage progression information from the phase plot of the thermal images .In future work, active and passive thermography will be used to study the damage evolution in CFRP specimens with different layups.

6. References

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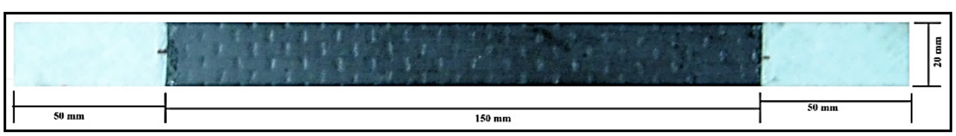

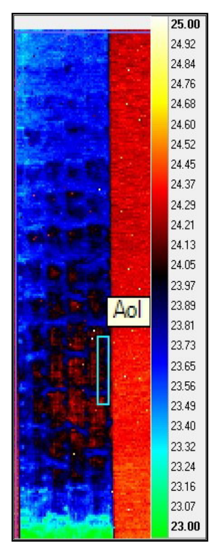

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7. Figures:

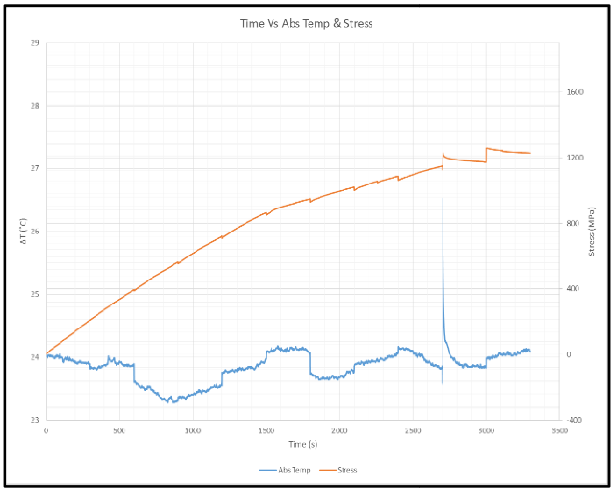


Figure 5: Absolute temperature and stress curves with respect to time, considering mean temperature of AoI.

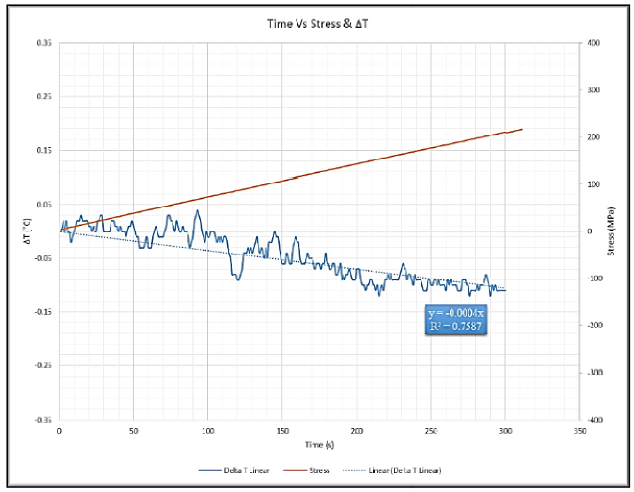


Figure 6: Zoomed linear zone of ΔT (°C) –Zone I

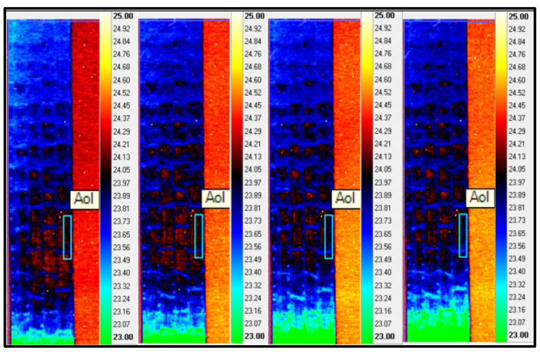


Figure 7: For Zone I, temperature decrease linearly at AoI (Frames are at t (sec) = 0, 20, 40 & 60 resp.)

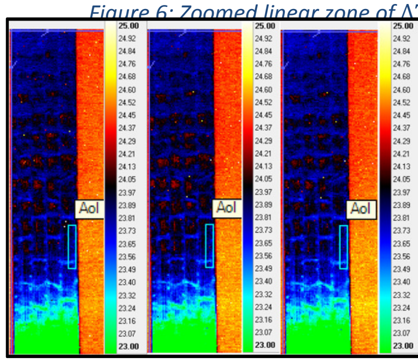


Figure 8: For Zone II, temperature decrease Non-Linearly at AoI (Frames are at t (sec) = 80, 120, 726 & 1020 resp.)

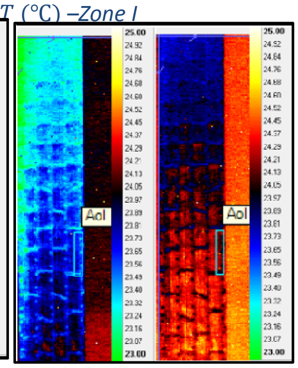
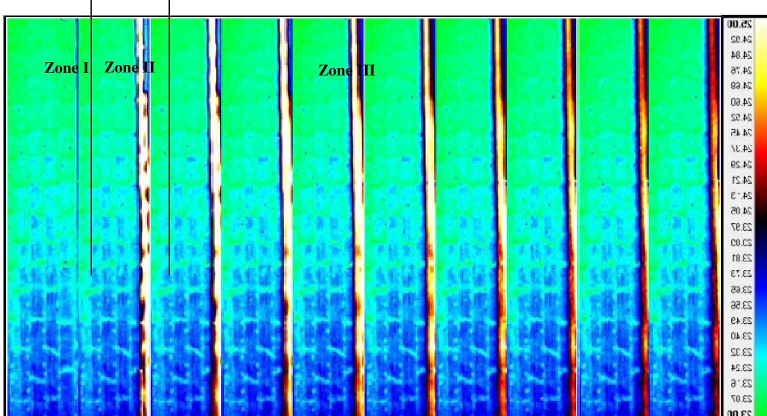


Figure 9:For Zone III, temperature increase at AoI (Frames are at t (sec) = 1204 & 1241 resp.)



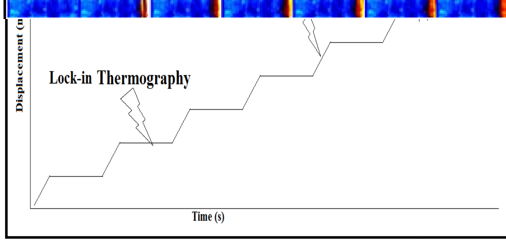


Figure 2: Load steps for tensile test

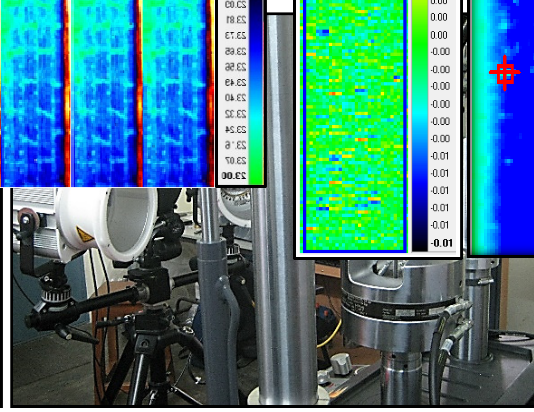


Figure 3:MTS & FLIR setup, for both Lock-in andpassive thermography

Figure 4: selected Area of Interest (AoI) with in the specimen

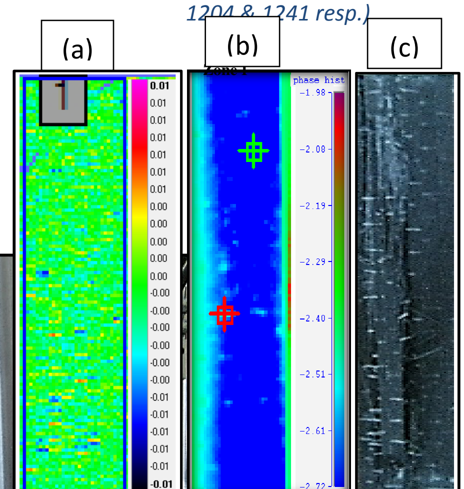


Figure 11: (a) Normalized- Subtracted image, (b) Lock-In phase image and(c) failure sample.

Figure 10: Catastrophic failure took place at AoI start at t=1081sec